# The Response of The Upper Ocean To Monsoonal Forcing

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## LONG-TERM GOAL

The ultimate goal of my research is a complete characterization of the upper ocean's response to atmospheric forcing. The forcing takes place through surface fluxes of heat, fresh water and momentum. The response may be local and direct, or may be modified by advection and wave propagation.

## OBJECTIVES

The scientific objective of my effort is the observation of the oceanic response to the Arabian Sea monsoons. The primary technological objective is the development of a light-weight meteorological package for deployment on a surface mooring. The Arabian Sea is an attractive region for an air-sea interaction experiment because of the strength and steadiness of the monsoons. The wind-stress spectrum is more energetic at low frequencies in the Arabian Sea than in mid-latitude locations where the forcing is dominated by storms. The Arabian Sea ARI thus provides an interesting contrast to previous experiments done at higher latitudes such as LOTUS, FASINEX, and Ocean Storms.

## APPROACH

My experimental approach has been to deploy two surface moorings as part of a five-mooring array in collaboration with R. Weller of WHOI and C. Eriksen of UW. An SIO mooring includes a surface buoy carrying a meteorological package (MARMET) measuring wind speed and direction, short-wave radiation, air and sea temperatures, and atmospheric pressure. The buoy bridle holds a downward looking 300 kHz Acoustic Doppler Current Profiler (ADCP) measuring horizontal velocity in 4 m bins down to 120 m. Temperature recorders are positioned at 10 m intervals in the upper 50 m and 20 m intervals from 50 to 150 m. My approach in analyzing the data is to use appropriate statistical methods to isolate the ocean's response to the monsoons.

## WORK COMPLETED

The two moorings were successfully deployed during a cruise in October 1994, turned around in April 1995, and recovered in October 1995. Overall data recovery was excellent. All meteorological data on all buoys were returned except for wind during the first deployment of the southern buoy. The wind sensor electronics failed during a strong storm, presumably due to a lightning strike. The overall data return of meteorological variables was thus 95%. The ADCPs worked flawlessly so that horizontal velocity data return was 100%. All temperature recorders worked perfectly during the first six months. Unfortunately, we suffered some failures and losses during the SW monsoon. Five recorders were stripped from the mooring line on the north mooring, two recorders had short records, and one was recovered with the end caps and electronics gone. In spite of the problems, overall temperature data return was 82%. Weighting meteorological variables, currents, and temperatures equally, the data return on the two SIO moorings was 92%. An initial report on the unprecedented one-year moored observations has been published in Rudnick et al. (1997).

**RESULTS**

The past year has been devoted to finishing data analysis and the preparation of manuscripts. Three manuscripts are now in preparation, with submittal anticipated by the end of the calendar year. The results presented in the three manuscripts are discussed below.

The first manuscript is a general description of the 1994-1995 Arabian Sea monsoon as observed by the moored array: "Moored Observations of Upper Ocean Response to the Monsoon in the Arabian Sea During 1994-1995" is a collaboration among all the mooring investigators. During the NE monsoon winds were moderate, and the air was clear and dry. Sea surface temperature cooled by approximately 3°C due to surface heat loss and convection, and the mixed layer deepened to over 100 m. The SW monsoon had stronger winds peaking at over 15 m/s, and cloudy, humid skies. Even though the ocean gained heat from the atmosphere, the sea surface temperature dropped by roughly 5°C and the mixed layer deepened to over 70 m because of wind stirring. Upper ocean velocity was dominated by mesoscale geostrophic flows which sometimes made upper ocean balances of heat and salt strongly three-dimensional.

A second manuscript focuses on the momentum balance during the monsoons: "The upper ocean momentum balance during the Arabian Sea monsoons." A one-dimensional momentum balance works quite well during the first half of the SW monsoon, yielding a velocity spiral and a transport that agrees well with the theoretical Ekman transport. This one dimensional balance works well on time scales as short as a few days. The wind-driven flow penetrates approximately 20 m deeper than the mixed layer as determined by temperature (Figure 1). This result has important implications for the calculation of heat transport from large-scale measurements of wind-stress and temperature since the wind will tend to move colder water beneath the mixed layer, especially when the mixed layer is shallow. The most energetic part of the shear spectrum is the inertial band. Shear in the inertial band is concentrated just below the base of the mixed layer. This shear penetrates downward as the mixed layer deepens. This shear is ultimately driven by the wind, and on one occasion during the SW monsoon escapes the base of the mixed layer because the wind has a strong inertial component. This result is relevant to the distribution of mixing in the ocean, because inertial shear is the likely energy source for turbulent dissipation.

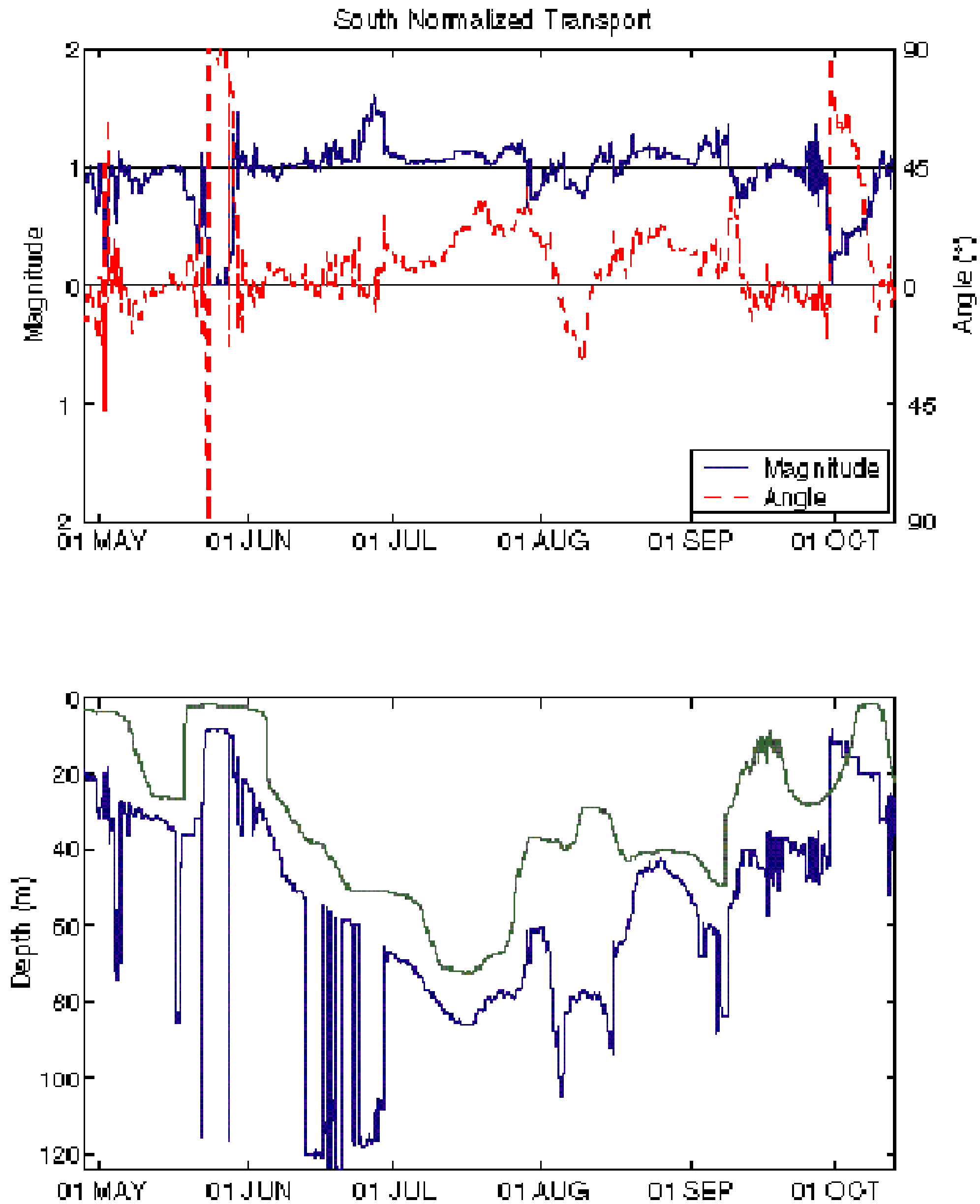


***Figure 1. Top panel: Observed wind-driven transport normalized by the theoretical Ekman transport. Perfect agreement with theory would have a magnitude of one and an angle of zero. Bottom panel: Mixed-layer depth (green) and depth of wind-driven layer (blue). The wind-driven layer is 23 m deeper than the mixed layer on average.***

The third manuscript examining the 1995 SW monsoon onset in detail is a collaboration with Maria and Piotr Flatau. The 1995 onset occurred in two stages, with the wind veering to the SW at the beginning of May and a shutoff of the wind two weeks later. The final onset occurred near June 1, and the monsoon blew until September. We relate this double onset to sea surface temperature in the Arabian Sea, and atmospheric Rossby waves propagating between the equator and the Bay of Bengal. Double onsets occur every several years, and the 1995 event was the most striking one yet observed. Prediction of the monsoon onset is crucial for the countries that depend on monsoonal precipitation.

## IMPACT/APPLICATION

These observations comprise the first year-long time series of the oceanic response to the Arabian Sea monsoons. The Arabian Sea provides a nearly ideal laboratory for studying the response to a steady wind. In this case the steady wind produced convincing evidence of a nearly instantaneous Ekman spiral. The penetration of wind-driven momentum beneath the mixed layer is relevant to estimates of wind-driven heat transport, and to the modeling of vertical momentum flux. The global distribution of inertial shear must be known to predict inhomogeneity in ocean mixing. The use of ADCPs such as done here will be important to this effort.

## TRANSITIONS

Our marine meteorological system MARMET forms the central suite of meteorological measurements on the SIO Marine Observatory "monster buoy."

## RELATED PROJECTS

The ONR Arabian Sea mooring investigators, R. A. Weller, C. C. Eriksen, T. D. Dickey, J. Marra, and myself are cooperating on the publication of a description of the oceanic response to the monsoons.

The collaboration with Piotr Flatau and Maria Flatau on the coupled response of the atmosphere and ocean during the monsoon onset is partly funded by NSF and NOAA.

## REFERENCES

Rudnick, D. L., R. A. Weller, C. C. Eriksen, T. D. Dickey, J. Marra, and C. Langdon, 1997: Moored instruments weather Arabian Sea monsoons, yield data. *Eos, Trans. Amer. Geophys. Union,* **78,** 117, 120-121.